Studies of Ionospheric Irregularities: Origins and Effects

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LONG-TERM GOALS

We have two long-term goals. The first goal is to understand the electrical properties of the upper atmosphere and space environment to better assist designers and users of space systems and technology. The second goal is to educate the next generation of leaders in space science and engineering.

OBJECTIVES

The scientific objectives of the project are:

(1) To investigate space weather and its effects on GPS including the characterization of L-band scintillations and scintillation effects on GPS signals and receivers
(2) To investigate the origin of ionospheric irregularities, which lead to ionospheric scintillation storms, through deployment of GPS scintillation receivers at equatorial latitudes, regionally in South America, at mid-latitudes (Hawaii, Ithaca, Puerto Rico, Utah), and at high latitudes (Norway);
(3) to develop GNSS receivers (WAAS, Galileo, and modernized GPS) that can assess the effect of scintillations and space weather on modernized GNSS signals;
(4) to develop space-based GPS receivers for sounding rocket and satellite applications that can remotely sense the ionosphere, thermosphere, and mesosphere.

Our research focuses on the study of space weather and the impact of space weather on GPS and GNSS receivers. Our approach is primarily experimental, and we have a reputation for producing cutting-edge instrumentation and developing successful experiments. The vast majority of the universe exists in a plasma state and we focus on our own upper atmosphere and ionosphere as natural laboratories for studying space weather and as an environment that affects satellites and their signals. This yields a mix of applied and curiosity-driven research. By primarily employing sounding rockets and ground-based instrumentation, graduate students are able to participate in the full range of research

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and develop into future leaders. For example, Cornell University development of a GPS receiver for measuring fast amplitude scintillations has led to a global program with receivers deployed at multiple sites across South America, Africa, and China. Several Ph.D. students and postdocs from Cornell and Brazil have been trained using these receivers. This receiver not only monitors ionospheric scintillation but additionally measures ionospheric drifts. This effort also leverages our development of GPS software receivers and space-based GPS receivers.

APPROACH

Our scientific strategy emphasizes experimental development. We have chosen this route because the field of space science, especially that investigating the electrical properties of space, is still experimentally limited. Theories of space physics and space plasma physics are quite plentiful, but discriminating measurements are few and far between. Within this context one may well ask what areas need the most attention. The answer concerns nonlinear problems involving plasma waves and electric fields in collisionless environments and turbulent media. Incidentally, these areas are also examples that, at one extreme, can test theories of basic plasma physics and, at the other extreme, are important for the development and application of new communication and navigation technologies.

For this research our approach has been first to develop a GPS receiver capable of measuring scintillations and other space weather effects. Our first receiver (SCINTMON) was also the first GPS receiver to measure fast L1 amplitude scintillations. Subsequently this design was copied by several other receiver manufacturers. The SCINTMON receiver has recently been upgraded to track WAAS signals. Our GPS receiver design continued with the development of digital storage receivers, which capture the entire GPS band width (L1 and L2), and software receivers that post-process or analyze the GPS signals. Currently we are developing real-time GPS software receivers on DSP chips. These receivers have been demonstrated on PC platforms. Dr. Psiaki and Dr. Humphreys are collaborators in this regard.

With the development of SCINTMON and digital storage receivers, the next step was to deploy them globally for measuring space weather effects, including scintillations. Our approach is to give GPS receivers away "free" to collaborators, who then operate the receivers in regions of geophysical interest and share their data with us. This approach has been highly successful and we have established a regional chain of roughly 20 GPS scintillation receivers in South America (mostly Brazil with Dr. Erico de Paula at INPE)) from the equatorial anomaly to the geomagnetic equator. Other receivers have been placed in Hawaii, Utah, Ithaca, Puerto Rico, Eritrea, Norway, and China. We are also extending our expertise in ground-based receivers to space flight. Three receivers were launched in a sounding rocket investigation of the northern lights and we are working with two colleagues (Dr. Mark Campbell and Dr. Mason Peck) at Cornell to create a GPS receivers for a micro and pico satellite projects. The CUBEsat instrument was designed to sense ionospheric scintillations of GPS signals in orbit for the first time. The CUSat uses our GPS receivers as part of the In-Orbit Inspection Nanosatellite Technology Flight Demonstration (INTech) project, which is funded by ONR. Both the CUBEsat and INTech projects use a GPS simulator acquired through DURIP funding.

WORK COMPLETED

(1) We learned that solar radio bursts are sufficiently intense to cause GPS receivers to temporarily fail, especially dual-frequency civilian receivers.

(2) We made the first ionospheric scintillation measurements of the GPS L2 signal and learned that for moderate scintillation the fades on both the L1 and L2 channels are simultaneous but deeper on L2.
(3) We made the first measurements of deep fades, greater than 20 dB, on the GPS L1 signal and learned that deep fades are accompanied by half-cycle phase flips. We further learned that the combination of deep amplitude fade and half-cycle phase flips causes receivers to cycle slip or stop tracking.
(4) We made the first total electron content (TEC) measurements using the L1CA and L2CS signals and learned that we can measure TEC with a relative accuracy of 0.01-0.02 TEC units (TECU) at 20 ms cadence. This corresponds to a relative ranging accuracy of 1.6 mm without the need to average.
(5) We created an ionospheric scintillation model that can be employed with GPS signal simulators.
(6) We published a major review paper entitled "GPS and Ionospheric Scintillations" in the journal *Space Weather*.

RESULTS

With respect to item 1, we have demonstrated that the solar radio bursts have significant effects on GPS receivers. During December 2006 there were three major solar radio bursts that affected GPS receivers. The most intense was on December 6, 2006, with the solar radio burst intensity reaching nearly 1,000,000 SFU at L1. In cooperation with Dr. Dale Gary, who is the PI for Owens Valley Solar Array (OVSA), we were able to compare solar radio burst power with GPS L1 carrier-to-noise ratios (C/No). Figure 1 shows one such comparison using an FAA WAAS receiver. The WAAS receivers were chosen because they employ atomic clocks to reduce clock phase noise and narrow bandwidth tracking loops to reduce band noise. These are arguably the most robust GPS receivers in operation and mostly continued to track during the large solar radio burst.

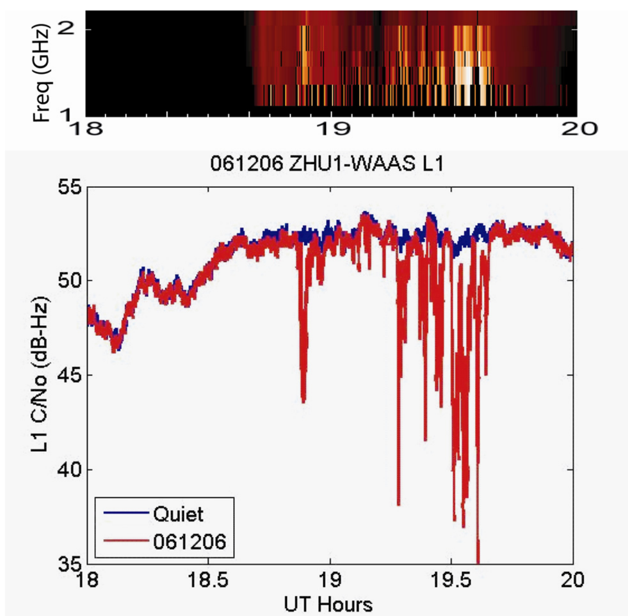

Figure 1. A comparison of solar radio power between 1 GHz and 2 GHz to L1 C/No for a WAAS receiver in Houston, TX. For the largest solar radio burst power, the largest decreases in C/No occur with a maximum decrease of 16-17 dB.

Figure 1 shows the response of an FAA WAAS receiver in Houston, TX in the top panel and a spectrogram of solar radio burst power from the OVSA in the top panel. The blue line is the measured C/No for the previous sidereal day and the red line is measured C/No corresponding to the spectrogram in the upper panel. By comparing the two panels, it is obvious that the more intense solar radio burst power corresponds to reduced C/No, with the largest reductions of C/No being 16-17 dB.

Another example shows the response of IGS network receivers to this solar radio burst. Figure 2 shows (as green dots) IGS receivers that are tracking at least four GPS satellites in the upper panels. When the receivers track fewer than four GPS satellite signals, they become red dots. In the lower panel is the solar radio burst power as a function of time with a red dot showing the time and intensity of the solar radio burst corresponding to the upper panel. In the first panel the solar radio burst power is small and all of the IGS receivers are tracking successfully. In the middle panel when the solar radio burst power is strong, about half the IGS receivers in the sunlit hemisphere are not successfully tracking at least 4 satellites. In the last panel during a second intensification of solar radio burst power, about half of the receivers in the sunlit hemisphere again are not tracking at least four satellites.

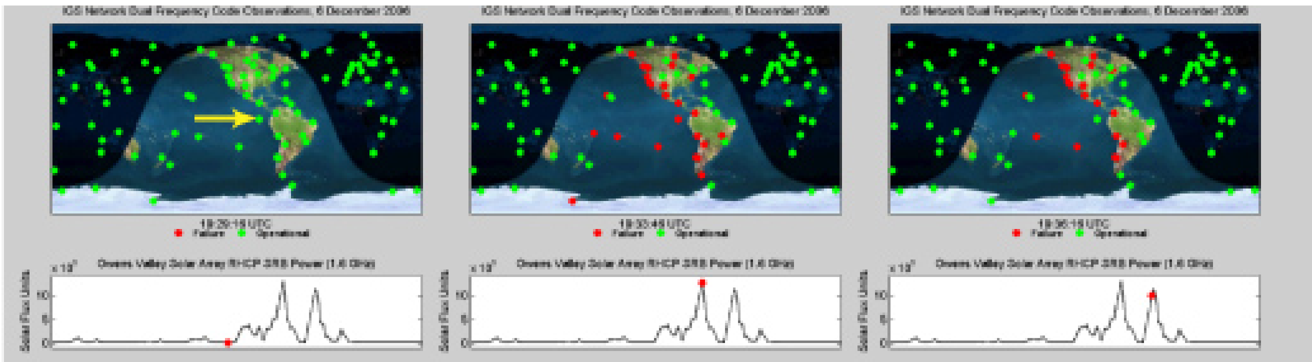

Figure 2. A comparison of solar radio burst power at L1 with the tracking ability of IGS receivers. See text.

In addition to the demonstration of IGS receivers failing during the solar radio burst power, a NOAA memo confirmed that military grade GPS receivers were also failing. The memo states from GPSOC at Schriever AFB on 06 Dec:

"At approximately 6 Dec/2000Z there was a widespread loss of GPS in the Mountain States region, specifically around the 4 corners region of NM/CO. Several aircraft reported losing lock on GPS and were tracking 7-9 satellites, and abruptly loss [sic] locks and were then tracking 0-1."

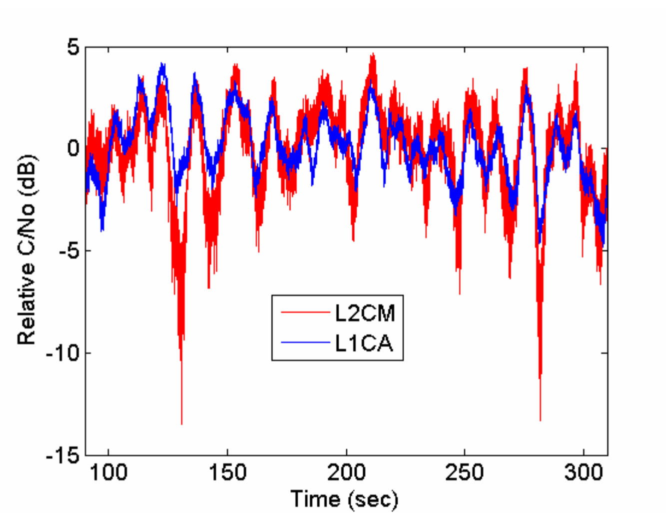

Figure 3. A comparison of GPS signal fades at L1 and L2. See text.

From these studies we learned that we do not understand the historical record of solar radio burst and that even at solar minimum solar radio bursts can be intense enough to affect GPS receivers. This fact implies that operational uses requiring truly continuous GPS service should not be employed.

With respect to item 2, we made the first ever scintillation measurements of the L2CS signal. Figure 3 shows an example of weak scintillations at L1 and somewhat stronger scintillations at L2. The two C/No amplitudes are shown for a little more than 200 s. The blue record is the L1CA amplitude and the red record is the L2CM amplitude. From the figure it is clear that the L1CA and L2CM fades are simultaneous but that the L2CM fades are larger than the L1CA fades. The L1CA fades are about 5 dB while the L2CM fades are up to 15 dB. This implies that the L2 signals are more vulnerable to scintillation.

With respect to item 3, our pioneering use of the digital storage receivers to measure GPS signal scintillations has made possible the full characterization of a deep fade for the first time. With standard GPS, receiver tracking would fail during a deep fade and the phase history would be lost. Using a digital storage receiver that captures and stores in memory the entire GPS bandwidth, we can analyze the signal with non-standard tracking techniques such as data wipe-off and tracking backwards in time.

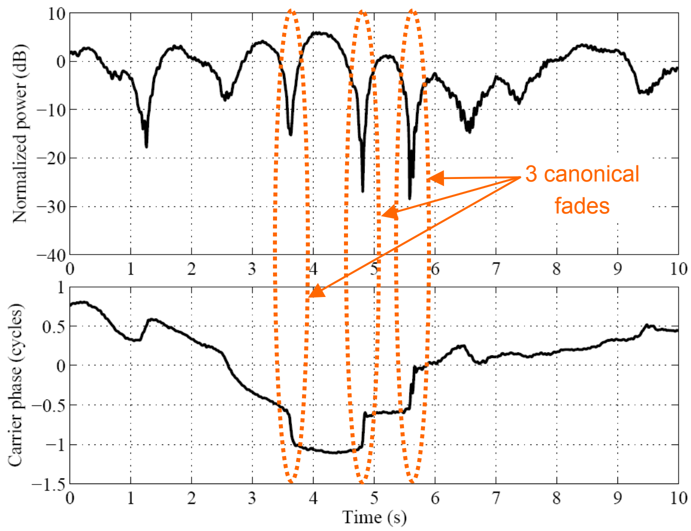

Figure 4. Amplitude and phase of a GPS signal during deep (> 20 db) fades showing coincident half-cycle phase jumps.

Figure 4 shows an example of the analysis on severe (S4=0.9) L1CA fades. Three of the canonical fades are circled, consisting of deep amplitude fades and coincident half-cycle phase flips. From this we learned that the effects of amplitude fades or phase scintillation cannot be separated when analyzing GPS receiver response to scintillation.

With respect to item 4, using digital storage receivers we made the first measurements of TEC using the L1CA and L2CM signals. Figure 5 shows an example of the relative phase between L2CM and L1CA over about 5 minutes. The measurements were made in Ithaca NY at solar minimum. The graph shows a slowly changing, linear phase advance of about 1 TECU over the five-minute period. The change in phase advance corresponds to the slant path change through a weak ionosphere. When the phase advance is detrended for the changing slant path, we demonstrated that the phase advance resolution corresponds to about 0.01 TECU at 20 ms cadence. From this study we learned that it will be possible to make very precise space weather GPS receivers using the L2CS signals.

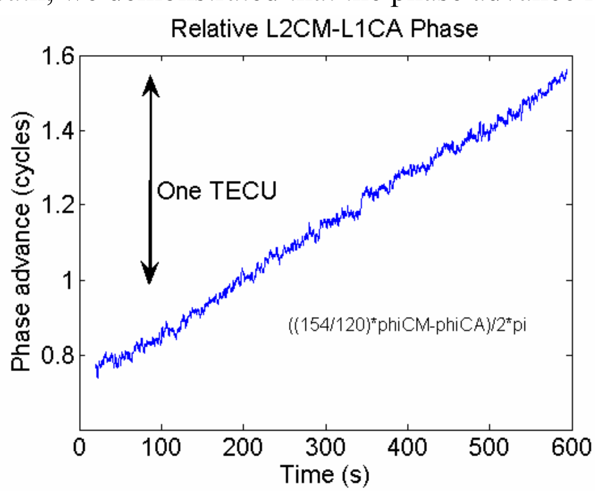

Figure 5. The relative phase between L2CM and L1CA produced by propagation through the ionosphere. See text.

With respect to item 5, we have created a scintillation model based on forward scattering of GPS signals to be using in GPS signal simulators. Figure 6 shows the example of the fades produced by the scintillation model. This is an example of weak scintillations with S4=0.16 where the C/No amplitude in dB is shown over an 8 km baseline. The fades for both L1 and L2 are shown and the L1 fades are stronger, as expected from item 2 above. The L1 fades are about 4 dB while the L2 fades are about 8 dB. We are working with Spirent Communications to develop a user-friendly adaptation of the scintillation model for their GPS signal simulators.

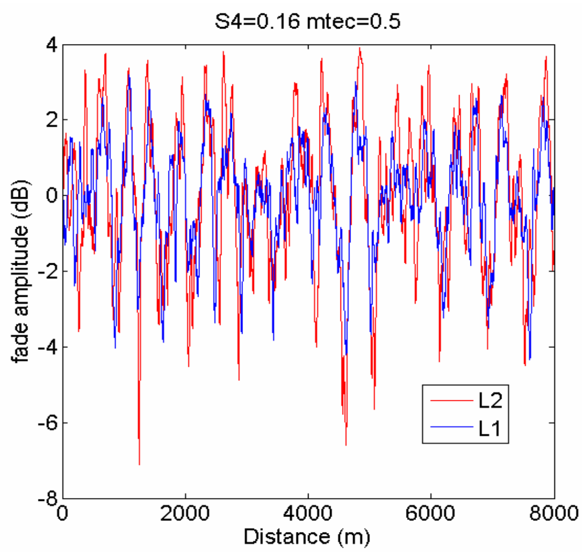

Figure 6. Scintillation fades on L1 and L2 produced by a forward-scatter model.

With respect to item 6, we completed a major review paper on GPS and Ionospheric Scintillations that can be found at:

GPS and ionospheric scintillations, P.M. Kintner, B.M. Ledvina, and E.R. de Paula, *Space Weather*, *5*, S09003, doi:10.1029/2006, 2007.

IMPACT/APPLICATIONS

Our work with GPS receivers and Space Weather continues to be important in understanding and predicting the behavior of GPS receivers in the presence of both solar radio bursts and scintillation. In the future our receivers will be critical to evaluating the impact of space weather on GNSS signals. Our past work in determining the shape of fade patterns is important to understanding how velocity resonance will occur and potentially produce loss of lock or even loss of navigation in GPS receivers. Our recent work with the WAAS signals will lead to understanding the significance of scintillations on this system. Our continued development of software receivers looks to the future when modernized GPS signals will be available and dual-frequency measurements of TEC should be inexpensive.

We have demonstrated the GPS receivers are vulnerable to solar radio burst and that this will likely cause brief (10-30 minutes) receiver outages during the next solar maximum.

We have demonstrated that scintillation fades on L2 are more severe than on L1.

We have demonstrated that scintillation during deep fades has canonical behavior. That is, deep fades are accompanied by half-cycle phase jumps. This will lead to more robust tracking loops that can take into account the rapid phase changes.

We have demonstrated that TEC can be measured very accurately using the L1CA and new L2CS codes. This will lead to less expensive, more accurate, and more robust GPS receivers for a variety of applications such as space weather monitoring of TEC, satellite drag, and scintillation measurements.

TRANSITIONS

We are working with Spirent Communication to transition our scintillation model to their GPS signal simulators. We have received STTR funding from ASTRA, Inc. (http://www.astraspace.net/) to develop a DSP-based GPS space weather receiver.

RELATED PROJECTS

Our NASA projects depend heavily on the funding of GPS receiver development. For example, the results from the ground-based GPS scintillation receivers were critical in determining goals for the LWS/Geospace Mission Definition Team report. The sounding rocket program at Cornell uses GPS receivers originally based on the scintillation receiver design. http://lws.gsfc.nasa.gov/docs/Geospace/GMDTReportforWeb.pdf

The CUBEsat and CUSat programs, with which we are collaborating, uses a receiver based on the Cornell sounding rocket design and the GPS signal simulator, purchased with DURIP funding, is being used to develop and test the CUBEsat and CUSat GPS receivers. Further information can be found at http://www.mae.cornell.edu/cubesat/ and http://cusat.cornell.edu/.

We collaborate closely with Prof. Michael Kelley (Cornell) and Dr. Jonathan Makela (NRL), who make all-sky ionospheric images. Several joint papers have been published using imaging and GPS data at Hawaii. See http://www.cosis.net/abstracts/EAE03/05826/EAE03-J-05826.pdf.

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PATENTS

Real-Time Software Receiver, January 10, 2003. U.S. patent issued 2006. **Patent number** 7010060

HONORS/AWARDS/PRIZES

The following paper received "The Best Presentation Award" at the ION GPS Conference in Portland, Oregon, Sept. 2002:

Powell, S., E. Klatt, and P. Kintner, Plasma wave interferometry using GPS positioning and timing on a formation of three sub-orbital payloads.

ION GNSS 2006 Best Student Paper Award

Cerruti, A., Observed GPS and WAAS signal-to-noise degradation due to solar radio bursts.